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ABSTRACT

The National Center of the U.S. Geological Survey in suburban Washington, DC is a seven story building containing both office and laboratory space. Based on a history of occupant complaints regarding the air quality within the building, an investigation was conducted by the National Institute of Standards and Technology to quantify the ventilation characteristics of the building and to determine the indoor levels of selected indoor pollutants. The investigation of the building included measurements of air exchange rates using the tracer gas decay technique and measurements of indoor concentrations of carbon dioxide, carbon monoxide, radon, formaldehyde and particulates. The measurement results are compared to appropriate standards and guidelines in order to investigate the role of ventilation and pollutant concentrations in the indoor air quality complaints. The additional issues of local distribution of ventilation air, entrainment of exhaust air, and thermal comfort were also examined. Based on the investigation, several recommendations are made to improve the environmental conditions within the building.

Key Words: air quality; building diagnostics; building performance; indoor air quality; tracer gas testing; ventilation.

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1. INTRODUCTION

The John Wesley Powell Federal Building, the National Center of the United States Geological Survey (USGS), in suburban Washington, DC is a large complex containing both office and laboratory space. This building has had a history of indoor air quality complaints by some of its occupants including poor thermal comfort, odors, and typical "sick building" symptoms of eye irritation, respiratory complaints, headaches, and general discomfort. Most of the complaints are associated more with certain areas in the buildings than others, and many of them are episodic, occurring only on specific occasions. In an attempt to understand the source of these complaints within the building, the USGS entered into an interagency agreement with the Center for Building Technology of The National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) to evaluate the building's ventilation performance and to measure the levels of several indoor air pollutants. The goal of this investigation was to examine these building characteristics and to compare the measured ventilation rates and pollutant levels to appropriate standards and guidelines to determine if they were at reasonable levels. Other aspects of the building ventilation and air quality characteristics that may be related to the occupant discomfort were considered in a more qualitative manner. These include distribution of ventilation air within the building, thermal comfort, entrainment of exhaust air by the building ventilation system, and other issues of intake air quality.

Indoor air quality complaints have become more common, or at least more well publicized, in recent years. Whether or not the indoor air quality within buildings has actually worsened is not known, however, the awareness of building occupants and managers with regards to these complaints has increased. Although there has been insufficient research to establish the physical causes of these complaints, several reasons have been suggested including the introduction of materials into buildings that release irritating, if not hazardous, substances and the reduction of building ventilation rates in order to save energy. In fact, the actual ventilation rates that exist in buildings have not been well characterized, and therefore such general statements about ventilation rates in existing buildings and trends over time in building ventilation rates can not be supported [Persily 1989].

Building air quality investigations are being conducted by research organizations and commercial companies using varying levels of detail and sophistication, but there is not yet any standardization of the protocols employed in these investigations. Building air quality is a very complex field, and there are a large number of factors that can be important in any given building. These include the ventilation and air distribution system design and operation, materials and activities within the building, outdoor air quality, and so-called "psychosocial" phenomena related to the satisfaction of the building occupants with their physical environment and work. Most indoor air quality investigations have involved only one, or a limited number, of these complex and interacting factors. In

particular, many studies of indoor pollutant levels have not included measurements of ventilation rates and other aspects of building air exchange performance. Given the obvious importance of ventilation, and the fact that it is commonly blamed for air quality problems, this is an unfortunate shortcoming of many indoor air quality studies. Ventilation rate measurement and ventilation system performance evaluation is important to determine if the building in question is being operated as designed and if the ventilation rates are sufficient according to appropriate ventilation standards and guidelines. However, the indoor concentration of any substance depends on the generation rate of that substance and the ventilation rate of the building, and therefore providing a given ventilation rate can not by itself guarantee that indoor pollutant levels will be below any specific level. Such assurance necessarily involves the knowledge and control of pollutant sources strengths, as well as other factors.

The USGS investigation was designed to evaluate several physical aspects of the building's ventilation and air quality performance in order to determine their relation to the indoor air quality conditions within the building. Building air exchange rates were measured under a variety of building operation conditions to determine if they were adequate according to relevant standards and guidelines. The indoor levels of several airborne substances were also measured in this investigation and compared to relevant standards and guidelines. The pollutants that were studied include carbon dioxide, carbon monoxide, radon, formaldehyde and particulates. In addition to these quantitative measurements, the study also investigated other important aspects of the building's ventilation and air quality performance that may be contributing to the occupants complaints including interior air distribution, intake air quality, and thermal comfort.

1.1 Building Description

The USGS Building was constructed in 1974 and is located on a 105 acre site in a suburban area near Washington, DC. A photograph of the building is shown in Figure 1, and a floor plan is shown in Figure 2. The builidng contains both office and laboratory space, and is divided into three main sections: a seven-story administration section, which contains predominantly office space; a five-story laboratory section, which contains both laboratory and office space; and a two-story printing plant that is connected to the laboratory section of the building by an elevated walkway. There is a single basement level throughout the administration and laboratory sections. The seven-story administration section has an occupiable floor area of approximately 28,000 m^2 (300,000 ft^2) and is served mainly by five supply fans that operate during the occupied hours of the day (approximately 6 a.m. to 6 p.m.), except for the cafeteria supply fan which operates from 5 a.m. to 2:30 p.m. The total capacity of the five main fans is 140 m^3/s (300,000 cfm), corresponding to about 6 air changes per hour (ach). The occupiable floor area of the five-story laboratory section is approximately 43,000 m^2 (460,000 ft^2). About twenty supply fans serve this area, three that operate twenty four hours a day everyday and the

rest that operate during occupied hours or as needed. Ten of these fans serve the main occupied areas. The total capacity of these ten fans is 240 m^3/s (510,000 cfm), about 6.5 ach. The remaining supply air fans provide make-up air for laboratory exhaust ventilation systems, or ventilate mechanical and electrical rooms and other small areas within the building. The printing plant has a floor area of approximately 12,000 m^2 (120,000 ft^2) and is served by five supply fans with a combined flow rate of 80 m^3/s (170,000 cfm), yielding a design ventilation rate of 7.8 ach. The above fan capacity specifications are for total ventilation air, including both outdoor air intake and recirculated return air. Specifications for the outdoor air intake rates for the building air handlers are unavailable.

All of the fans are variable air volume systems, and are located in several basement level mechanical rooms, except in the printing plant where they are located in a mechanical room on the first floor of the plant. Economizer controllers are used to determine the amount of outdoor air intake for most of the fans serving general occupied space. When the outdoor temperature is below 21°C (70°F), the economizer control system regulates the position of the outdoor air intake, exhaust, and recirculation dampers to maintain the supply air temperature at a predetermined setpoint. When the outdoor air temperature is greater than 21°C (70°F), or below 2°C (35 °F), the outdoor air intake is reduced to a minimum level. Some of the supply fans always operate at one hundred percent outdoor air intake, or at airflow rates designed to meet the exhaust air requirements of exhaust fans and fume hoods.

Both the outdoor air intakes and the general building exhausts are located at ground level, around the perimeter of the building, as shown in Figure 1. Some of the intakes are in close proximity to potential pollutant sources such as the emergency generators, the trash dumpsters, and the loading dock. All of the intakes are susceptible to pollutant sources associated with outdoor activities such as grass-cutting and fertilizing. The cafeteria loading dock is located near the intakes of air handlers SA-2,3,6 and 7. The exhaust outlets of the laboratory fume hoods and other dedicated exhaust vents are all located on the building roof.

1.2 Occupant Complaints

The ventilation and air quality investigation of this building was conducted because of the existence of numerous complaints in the building. These complaints have included odors, poor thermal comfort, stuffiness, poor air circulation, and typical "sick-building" symptoms including eye irritation, respiratory complaints, headaches and general discomfort. Most of the complaints have been episodic in nature, occurring with no apparent temporal patterns, and certain areas within the building have been associated with more of these complaints than others. Table 1 is a list of the rooms identified by USGS as needing air quality testing. This table includes the corresponding complaints in each area, as reported by the occupants, and the air handler serving the area. Testing was also requested in several areas associated with no specific complaints. This list of complaints does not constitute a systematic sampling of occupant satisfaction with the building's conditions, but only an anecdotal description of occupant reactions. The dominant complaints noted in this table are headaches, odors, poor air distribution and inadequate fresh air supply. The complaints in Table 1 appear to be associated with several specific air handling systems, SL-1,2,3 and 13 and SA-1 through 4. SL-13, associated with automotive exhaust odor complaints, is located just to the south of the building's loading dock.

2. MEASUREMENT TECHNIQUES

The building investigation involved the measurement of whole building air exchange rates and indoor pollutant concentrations. The air exchange rates were measured using the tracer gas decay technique, and the concentrations of several pollutants were measured using techniques appropriate to each individual substance. The pollutants that were studied include carbon dioxide, carbon monoxide, formaldehyde, radon and radon decay products, and particulates.

2.1 Air Exchange Measurements

The building air exchange rates were measured using the tracer gas decay technique [ASTM 1984]. These measurements were intended to determine the sufficiency of the outdoor air ventilation rates in relation to relevant ventilation standards. In the tracer gas decay technique a tracer gas is injected into a building and allowed to mix with the interior air. The tracer gas concentration within the building is then monitored over time. The measured decay rate of the interior tracer gas concentration can then be used to determine the air exchange rate of the building during the measurement period. The tracer gas decay procedure is based on the assumption that the tracer gas is well-mixed with the interior air, i.e. that the building tracer gas concentration can be characterized by a single value. A uniform interior tracer gas concentration can be facilitated by careful injection of the tracer gas such that it is well distributed throughout the interior of the building. The required uniformity of the interior tracer gas concentration must be verified by measuring the tracer concentration at many locations throughout the building interior.

In the tracer gas decay measurements in the USGS Building sulfur hexafluoride (SF_6), a harmless and inert tracer gas, was injected into the building supply fans every two hours, whenever the air handlers were running. The tracer gas was then allowed to mix with the interior air for roughly one-half hour, and the decay in tracer gas concentration in the main return fans was then monitored. During these measurements the tracer gas was injected into 18 of the supply fans, and the tracer gas concentration was measured in 13 of the return fans serving both the laboratory and administration sections of the building. Injection of the tracer gas in all of these supply fans provided a relatively uniform tracer gas concentration within the building, which was verified by the multipoint sampling of the SF_6 concentration. Because the tracer gas concentrations were measured in the return ducts, the air exchange rate measurements were only possible when the fans were in operation. The results of these measurements are average building air exchange rates over periods of roughly one and one-half hours.

These tracer gas measurements of air exchange employed an automated measuring system that enabled the collection of large amounts of data, under a range of outdoor weather and building operation conditions. Large numbers of air exchange

measurements are necessary to characterize the air exchange of a building because building air exchange rates are dependent on weather conditions and mechanical ventilation equipment operation. The automated measuring system has been used previously to provide continuous measurements of building air exchange rates [Persily and Grot 1985]. The system is based on a microcomputer that controls the tracer gas injection and air sampling, records the SF_6 concentrations, and monitors and records the outdoor weather, indoor temperature and fan operation status. The SF_6 concentrations were measured with a gas chromatograph equipped with an electron capture detector that determines SF_6 concentrations in a range of about 5 to 300 parts per billion with an accuracy of roughly 1%. Figure 3 is a photograph of the tracer gas measurement system installed in one of the building's mechanical rooms.

The air exchange rate measurements determine the rate at which outdoor air enters the building divided by the building volume, in units of air changes per hour (ach). This rate includes both air exchange due to the intentional intake of outdoor air through the air handlers and uncontrolled, unintentional air leakage through the building envelope (infiltration). Even in newly constructed office buildings, the rate of building envelope air leakage can be of the same order of magnitude as the rate of intentional intake of outdoor air [Persily and Norford 1988]. The decay measurements alone determine only the total air exchange rate and do not allow the distinction between these two sources of air exchange. Whole building air exchange rates were measured in the building during the fall of 1987, the 87/88 winter, and the spring and summer of 1988. A total of 228 air exchange rate measurements were made in this building during the investigation.

These tracer gas decay tests provide estimates of the whole building air exchange rates, but do not provide any information on the distribution of this ventilation air within the building. Nonuniformities in air distribution within buildings, e.g. rooms or locations within rooms that are less well ventilated than other portions of the building, have been suspected as being responsible for some indoor air quality complaints. There are no accepted measurement techniques for quantifying the uniformity of air distribution, and therefore the actual air quality impacts of such nonuniformities has not been demonstrated. However, because of the possible importance of air distribution, and the occupant complaints about poor air distribution, local air exchange characteristics were investigated to the extent possible. To this end, several locations within the building were subjected to measurements of local tracer gas decay rates during the whole building decay tests. In these tests, air samples were collected periodically at specific locations within the building during the whole building decay tests. Five or six air samples were collected at each location, at roughly 20 minute intervals. The tracer gas concentrations in these air samples were determined after the test and compared to the tracer gas concentrations measured at the same times in the return fan serving each area. The decay rate, in units of air changes per hour, were calculated at these locations and compared to the value obtained for the corresponding return air fans during the same period of time. Differences in the measurement results for these locations and the return

fan would be indicative of nonuniform distribution of supply, and outdoor, air at these locations relative to the rest of the building. However, the decay rate at any specific location is not a quantitative measure of the ventilation rate at that location. Tracer gas decay testing can be used to determine building air exchange rates if and only if the tracer gas concentration is uniform throughout the building being tested. The existence of significant nonuniformities in tracer gas concentrations violates this crucial assumption. The existence of differences in tracer gas concentrations and decay rates between a specific location and the return fan serving that location can at best provide a qualitative indication of the existence of nonuniform supply air distribution at these locations. These measurements of local decay rates were made in several of the areas which were reported to have high levels of occupant complaints (see Table 1).

2.2 Pollutant Concentration Measurements

The concentrations of selected pollutants were measured in the building. Carbon dioxide (CO_2) concentrations were measured because of their relation to the adequacy of ventilation in relation to building occupancy levels. While indoor levels of CO_2 rarely reach levels of concern within buildings, they are thought to provide an indicator of the adequacy of outdoor air ventilation levels [Salisbury 1986]. ASHRAE Standard 62-1981 [ASHRAE 1981] recommends that indoor CO_2 levels be maintained below 2500 parts per million (ppm). The revised version of this standard (to be published in 1989) reduces this recommended maximum to 1000 ppm. Carbon monoxide (CO) was measured to determine whether the air within the building was being contaminated by motor vehicle exhaust from the loading dock or exhaust from the emergency generators. There have been complaints of odors within the building that could be associated with these sources, and CO was measured as a surrogate for these sources. ASHRAE Standard 62 bases its recommendation for maximum indoor CO concentrations on the outdoor air requirements in the National Ambient Air Quality Standards [U.S. Environmental Protection Agency] i.e., maximum CO concentrations of 35 ppm for one hour averages and 9 ppm for 8 hours averages. The 1989 revision reports that concentrations above about 10 ppm have been suggested as being of limited concern.

Carbon monoxide (CO) and carbon dioxide (CO_2) were measured with an automated monitoring system, shown with the tracer gas system in Figure 3. The CO/CO_2 system employs two infrared absorption analyzers for determining CO and CO_2 concentrations and a microcomputer to switch among the sampling locations and record the data. The system determines CO and CO_2 concentrations at ten locations, with each location monitored once every ten minutes. The ten sampling locations included the nine main return ducts and an outdoor air sampling site on the building roof. The CO_2 monitor has a range of 0 to 2500 parts per million (ppm) and is accurate to within +/- 0.5% of full scale. The CO monitor has a range of 0 to 50 ppm and is accurate to within +/- 2% of full scale.

Particulate concentrations were monitored at several locations in the building with a light-scattering particle counter that determines particle concentrations in six different size ranges (0.3-0.5, 0.5-0.7, 0.7-1.0, 1-5, 5-10, and >10 μm). There are numerous and varied sources of particles both within and outside of any building. While the measured particle concentrations, in units of number of particles per m^3 of air, do not provide information on the composition of the particulate material, high concentrations are indicative of poor air quality. The particle counter operates in real-time, sampling from a single location. ASHRAE Standard 62 bases its recommendation for indoor particulate levels on the National Ambient Air Quality Standards which are in mass units, not particle concentration. ASHRAE adopted the NAAQS values for total suspended particulates, which includes a long-term average of 75 $\mu g/m^3$ over one year and a short-term average of 260 $\mu g/m^3$ over 24 hours. The NAAQS also includes a one-year average of 50 $\mu g/m^3$ and a 24-hour average of 150 $\mu g/m^3$ for particulates less than 10 μm. There is no straightforward conversion of the particle concentrations to mass units because of the variability in the composition and density of particulate matter. Particulate levels were monitored at ten locations in the building for periods of one-half hour to roughly one day.

Formaldehyde in buildings has been associated with some building materials and indoor activities and processes. It can be irritating at concentrations of about 0.1 ppm, with large variations in the sensitivity among people. ASHRAE Standard 62-1981 contains a guideline for formaldehyde concentrations not to exceed 0.1 ppm, based on continuous exposure. The 1989 version of this standard contains no such guideline, but instead reports that concentrations above about 0.1 ppm have been recognized as a level of concern. Formaldehyde concentrations were measured with passive monitors based on absorption onto a sodium-bisulfite treated filter and analysis by the chromotropic acid colorimetric method. These passive samplers yield average formaldehyde concentrations for periods from 5 to 7 days. Samplers were deployed at thirteen locations throughout the building and sent to an outside laboratory for analysis.

Radon gas enters buildings primarily from the ground and has generally not been thought to be a problem in mechanically ventilated, nonresidential buildings. Due to the building-specific nature of indoor radon concentrations, the small number of nonresidential buildings that have been studied, and the general concern about indoor radon, radon and radon progeny levels were measured in this building. Radon concentrations were measured at sixteen locations with charcoal canisters for periods of about 3 days, and at two locations with a working level monitor to obtain hourly measurements of radon progeny levels. ASHRAE Standard 62-1981 provides a guideline concentration for radon progeny of 0.01 Working Levels (WL), which converts to a radon concentration of approximately 2.5 pCi/L. The 1989 revision contains a guideline of 0.027 WL, about 7 pCi/L. The U.S. Environmental Protection Agency has an "action level" for radon of 4 pCi/L, meaning that some action should be taken in a building with concentrations above this level to reduce these concentrations.

3. RESULTS

This section presents the results of the air exchange and pollutant concentration measurements that were made in the USGS Building using the techniques discussed above. The measurement results are presented and discussed with reference to the building's air quality complaints and to relevant standards and guidelines.

3.1 Whole Building Air Exchange Rates

Whole building air exchange rates were measured using the tracer gas decay technique during each season of the year. As described earlier, these measurements involved injecting a tracer gas throughout the building and monitoring the tracer gas concentration decay rate at several locations in the building. The measurement technique is based on the assumption that the tracer gas concentration is uniform throughout the building. Tracer concentrations were essentially uniform within the administration and laboratory sections of the building, with slight differences between the two sections of the building. Therefore, tracer gas decay rates were calculated separately for these two sections of the building. Because of the slight differences in the tracer gas concentrations within these two sections of these buildings, these two tracer gas decay rates are not exactly equal to the air exchange rates of the respective sections, but do provide estimates of the air exchange rates. These estimated air exchange rates have an associated uncertainty of about 20%.

The results of the whole building tracer gas decay tests are shown in Figures 4 and 5 for the administration and laboratory sections respectively. These are plots of hourly average air exchange rates in these sections of the building versus the indoor-outdoor temperature difference. The air exchange rates in the administration section (Figure 4) exhibit a pattern that is common in office buildings [Persily and Grot 1985]. The air exchange rates are at a minimum during hot weather (lower indoor-outdoor temperature differences) in order to reduce the space conditioning load, i.e. the energy required to cool the outdoor air. At lower outdoor air temperatures, the air exchange rate increases because outdoor air is used to cool the building. As the outdoor air becomes even colder (larger temperature differences), less outdoor air is needed to cool the building and the air exchange rate again decreases. This building is characterized by very high air exchange rates relative to other buildings studied by NIST [Persily 1989], with a minimum air exchange rate of about 1 air change per hour (ach). The maximum air exchange rates measured in the administration section are about 3 ach. These measured air exchange rates include both the intentional air intake through the air handling systems and uncontrolled air leakage through the building envelope (infiltration). There is no way to know, based on these measurements, the relative proportions of these two contributions, but expected changes in the rate of intentional air intake do explain the pattern seen in

Figure 4.

The data in Figure 5 for the laboratory section exhibit a pattern that is similar to that seen in the administration section data, however the dependence on outdoor air temperature is less pronounced. The air exchange rates in the laboratory section change less than those in the administration section because many of the laboratory supply fans bring in large amounts of outdoor air at a constant rate in order to meet the ventilation requirements of the laboratories. The minimum air exchange rate in the laboratory is about 1.5 ach in cold weather and about 1.8 ach in hot weather. The maximum air exchange rate in mild weather is about 3 ach, as in the administration section.

The outdoor air intake specifications for this building are unavailable, and therefore it is not possible to compare the measured ventilation rates to the design values for outdoor air intake. The measured air exchange rates can, however, be compared to recommended levels of ventilation contained in ventilation standards. ASHRAE Standard 62 [ASHRAE 1981] provides recommended levels of outdoor air intake in a variety of spaces, including offices but not laboratories. The ASHRAE standard recommends 10 L/s (20 cfm) per person of outdoor air in office space when smoking is permitted and 2.5 L/s (5 cfm) per person in cases where smoking is not allowed in a space. The 1989 revision of this standard eliminates the distinction between smoking and nonsmoking spaces, recommending a ventilation rate of 10 L/s (20 cfm) per person in office space. In this building smoking is restricted to only limited area.

One may convert from L/s (cfm) per person to air changes per hour by dividing the per person ventilation level by the volume associated with each person. This conversion is approximate, since one must use an assumed value for the volume associated with each person. The ASHRAE standard provides a suggested value of occupant density that may be used unless a more accurate value is available. This default occupant density is 7 people per 100 m^2 (1000 ft^2), yielding a floor area per person of 14.3 m^2 (143 ft^2). To obtain the volume associated with each person one multiplies this floor area by the ceiling height. Because the return air in this building is recirculated, one must include the return air plenum in the ceiling height. Therefore, this floor area per person should be multiplied by a ceiling height of 3.5 m (11.5 ft). The resultant volume per person, 50 m^3 (1640 ft3), is therefore used to convert the ASHRAE ventilation recommendation to air changes per hour. Based on the above assumptions, this conversion yields a recommended ventilation rate of about 0.7 ach when smoking is permitted and slightly less than 0.2 ach when smoking is not allowed. All of the air exchange rates measured in this building are well above either level, and therefore, this building is well ventilated relative to the ASHRAE standard.

3.2 Local Tracer Gas Decay Tests

The whole building tracer gas decay tests discussed above provide information on the air exchange rates of the building as a whole, but do not provide any information on the uniformity of the distribution of this ventilation air throughout the building. Although the total amount of outdoor air brought into a building may be adequate on a whole building scale, if this air is not well distributed, there may be areas within the building with inadequate outdoor air supply. In order to obtain some indication of whether nonuniform air distribution is a problem in this building, local decay rates were measured at several locations in the building during the whole building decay rate measurements. While this procedure does not provide a quantitative indication of the ventilation rate associated with a particular location, it can provide a qualitative indication of the uniformity of the ventilation air distribution. If the local tracer gas concentration is significantly different from the response of the return fan serving the particular location being tested, then this can be an indication of nonuniform air distribution. A lower tracer gas decay rate in these areas could indicate poor ventilation air distribution at these locations.

Figure 6 shows three examples of the results of local decay tests. In each plot the logarithm of the tracer gas concentration at one or more of the test sites is plotted against time. The data in each plot corresponds to a specific room (or rooms) within the building (the distinct symbols in the graph) and the return fan serving the room(s) being tested (the solid line). In all of these plots, the concentration decay data for the individual rooms corresponds quite closely to the data for the return fan, indicating that the ventilation rate in these individual rooms is very close to that of the entire zone served by the corresponding return fan. While this information is qualitative, it does indicate good air distribution within the building. Table 2 shows the results of all of the local decay tests that were conducted in the building. A total of five tests are listed, and in each case the measured tracer gas decay rate is given for the test room and the return fan that serves that room. In almost all cases these two decay rates agree within the experimental uncertainty of about 20%. A few exceptions do exist, Room 4A108 in Test #2 and Room 2C310J in Test #4, in which the room decay rate is significantly higher than the return fan decay rate. The reason for this difference is not clear, but the fact that the room decay rate is larger, as opposed to smaller, than the return fan decay rate does not necessarily indicate poor air distribution in this room. A similar effect is seen in all of the rooms in Test #3.

The results of the whole building tracer gas decay testing indicate that the building is very well ventilated and generally quite well mixed. The local decay tests provide additional evidence that the interior air is well distributed, though it is possible that there are isolated areas in which the air distribution is poor. However, the rooms with complaints that were studied with this approach do not appear to have air distribution problems.

3.3 Pollutant Measurements

Measurements of indoor levels of carbon dioxide, carbon monoxide, particulates, formaldehyde and radon were made in the building in order to investigate the relationship between their concentrations and the building air exchange rate, and to determine how the measured levels compare to recommended levels for these contaminants. The measurement techniques used in this building were discussed earlier and the results are presented below.

3.3.1 Carbon Dioxide

Indoor levels of carbon dioxide were measured in the building return air ducts during the first four months of 1988. During all of these CO_2 measurements, tracer gas decay measurements of whole building air exchange rates were being made. The results of these measurements indicate relatively low levels of CO_2 in the building, consistent with the high air exchange rates that were measured. Figure 7 is an example of the CO_2 concentration profile for a day in the building, showing the concentrations in the administration and laboratory sections, the cafeteria and the outdoors for a single day with an air exchange rate of about 2 ach. In the administration and laboratory sections of the building, the CO_2 concentrations start at the outdoor level in the early morning and reach a maximum by about 10 a.m. The maximum in the administration section is higher than in the laboratory, typical for this building. A slight decrease in concentration occurs in the administration section corresponding to the lunch break, with a lesser decrease in the laboratory section. The cafeteria concentration reaches its peak during lunch, as expected, with smaller peaks during morning and afternoon breaks. The maximum CO_2 concentration on this day is about 425 ppm in the administration section, 410 ppm in the laboratory section, and about 475 ppm in the cafeteria. These levels are typical for this building, indicative of a sufficient amount of ventilation relative to the building occupancy levels. Figure 8 is a plot of the CO_2 concentration over several days, showing the repetitive nature of the pattern seen in Figure 7. The gradual, though slight, increase in concentration over the three days is due to a combination of an increase in the outdoor CO_2 concentration and a small drift in the calibration of the CO_2 monitor. Measurements of local CO_2 concentrations were also made with portable equipment on several occasions at the locations listed in Table 1, and the measurements were always consistent with the low levels found in the building return ducts.

The concentrations of CO_2 in this, or any other building, are determined by the CO_2 generation rate and the building ventilation rate. The generation rate in this building is essentially a function of the building occupancy level, since there is no indoor garage, indoor combustion, or other indoor sources of CO_2. Assuming the occupancy patterns are the same during most working days, the CO_2 concentration is determined primarily by the ventilation rate. Figure 9 is a plot of daily peaks of average CO_2 concentration in the

administration and laboratory sections of the building versus the daily average air exchange rate for the corresponding portion of the building. Each dot corresponds to a single day. The solid line represents the predicted maximum assuming an occupancy level of 7 people per 100 m^2 (1000 ft^2) and a constant CO_2 generation rate of 0.0053 L/s (0.011 cfm) per person. The predicted values are also based on the assumption that the CO_2 concentration is at equilibrium, i.e. the occupancy has been constant for a long enough period of time that the CO_2 concentration has built-up to its maximum level. The measured data agree with the predictions within expected experimental variations for air exchange rates above about 2 air changes per hour. At lower air exchange rates the measured maximum concentrations are below the predicted levels, with larger deviations at lower air exchange rates. This trend in the differences between measured and predicted maximum CO_2 concentrations is expected because at lower air exchange rates it takes longer for the CO_2 concentrations to attain equilibrium. For example, at 1 air change per hour, it takes more than three hours for the CO_2 concentration to attain its maximum value, and the lower the air exchange rate the longer it takes for the CO_2 concentration to reach equilibrium. In most office buildings, the occupancy levels are not constant for long enough periods of time for equilibrium concentrations to be achieved. Therefore, the lower the air exchange rate the greater the difference between the actual maximum CO_2 concentration and the predicted maximum value.

The CO_2 concentrations in this building, rarely above 500 ppm, are well below recommended maximum levels. The 1981 version of ASHRAE Standard 62 (ASHRAE 1981) has a recommended maximum CO_2 concentration of 2500 ppm, while the 1989 revision of this standard will reduce this recommendation to 1000 ppm. The levels in this building are well below either value, indicating that the building ventilation rates are more than adequate given the building occupancy levels. This finding is certainly consistent with the air exchange rate measurements discussed earlier.

3.3.2 Carbon Monoxide

The measured CO concentrations were generally quite low both within and outside of the building, approaching the lower limit of the CO monitor used in the measurements. In these situations the concentrations were essentially indistinguishable from the outdoor levels, on the order of 1 ppm. There were a small number of episodes when the interior levels were slightly elevated. Some of these were characterized by elevated CO concentrations in the intakes located near the loading dock on the east side of the building as well as in the return ducts of the fans associated with these intakes. During these episodes the CO concentrations attained no more than 10 ppm for short periods of time, less than one-half hour. These brief periods of elevated concentrations are suspected to be due to vehicle exhaust from the loading dock and weather conditions in which this exhaust is brought into the building through the air intakes located close to the

loading dock (see Figure 2) rather than dispersed by the wind. There were other brief periods of elevated concentrations in areas of the building associated with air intakes SL 1-4 on the west side of the building. These may have been due to vehicle exhaust at the cafeteria loading dock, or from the parking lot.

These episodes of elevated CO concentrations appear to require a combination of an outdoor source and appropriate weather conditions that allow the vehicle exhaust to linger near the air intakes. Because limited measurements of CO concentrations were made in the building, only a small number of these episodes were observed. The frequency of occurrence of these episodes is not known although their occurrence has been demonstrated. These events may be associated with the complaints of vehicle exhaust odors within the building. Entrainment of truck exhaust, as well as exhaust from the emergency generators and the power plant, are discussed further below.

As mentioned earlier, ASHRAE Standard 62 refers to the National Ambient Air Quality Standards (NAAQS) for CO in outdoor air. These standards contain maximum average CO concentrations of 35 ppm for one hour and 9 ppm for 8 hours. The applicability of these standards to nonindustrial buildings is certainly debatable, but nonetheless the levels measured in this building on the limited number of occasions discussed above are well within the NAAQS levels.

3.3.3 Particulates

Particulate levels were measured at 10 locations in the building with a light-scattering particle counter that determines particulate concentrations in 6 different ranges of particle size. Figure 10 shows a sample of the measured data, from a conference area in Room BC115, taken over approximately 24 hours. The six plots in the figure show particulate concentrations in units of particles per cubic meter in six size ranges: >10, 5-10, 1-5, 0.7-1, 0.5-0.7, and 0.3-0.5 μm in diameter. The horizontal axes in these plots is the time of day in hours, with the plot extending from approximately 9 a.m. on the first day to 9 a.m. the next day. The data are similar to those seen in other buildings in that the concentration variation in the larger particles (>5 μm in diameter) is greater than the variation in the smaller particles. The concentrations of these larger particles decreased to almost zero after the building occupants left, while the concentrations of the smaller particles decreased to a lesser extent after occupancy.

Table 3 summarizes the results of the particulate concentration measurements for the building. The concentrations are comparable with measurements that have been made by NIST in other buildings [Grot et al 1989]. Some of the lowest levels were measured in the computer room (2D113), which is expected given the effort that is made to clean the air in this environment. There are lower levels in the concentrations of particles greater than 5 μm in BC115, but this is because the measurement period in this room extends over unoccupied hours when the concentrations of the larger particles decrease to almost

zero. The highest levels of the large particulates were measured in the freight elevator lobby on the fourth floor. This could be an indication of air movement up the freight elevator into the occupied space of the building. This air movement could carry contaminants from the loading dock, such as motor vehicle exhaust, or from the trash bins outside of the loading dock.

Particulate level measurements are often given in units of mass per m^3 of air, and there is no accepted conversion of particulate concentrations in terms of number to mass units, only crude approximations. Such a conversion requires a value for the particulate density, but such a density will depend on the composition of the particulate matter. Assuming a density for the particulate matter as high as 5 g/cc, the measured particulate concentrations in this building convert to values below 20 $\mu g/m^3$. This is a relatively low particulate level compared with the NAAQS values for total suspended particulates of 75 $\mu g/m^3$ over one year and 260 $\mu g/m^3$ over 24 hours (50 $\mu g/m^3$ and 150 $\mu g/m^3$ for particulates greater than 10 μm in diameter), and with the values measured in other commercial buildings [Turk et al 1989]. Therefore, based on these measurements, elevated particulate concentrations do not appear to be a problem in this building. However, the chemical make-up of the particulate matter can be very important in determining the impact of any given particulate level.

3.3.4 Formaldehyde

Formaldehyde concentrations were measured at twelve locations in the building and at six additional locations at an off-site annex, Building E-1. These measurements employed passive monitors that were deployed at the locations for approximately 5 days. The results of the measurements are shown in Table 4. During the measurements in the main building, the air exchange rates were about 2 air changes per hour. The air exchange rates in Building E-1 were not monitored. All of the measured concentrations in the main building are below 0.03 ppm, and the concentrations in Building E-1 are only slightly higher. These concentrations are close to typical outdoor levels and the minimum detectable concentration of the monitors. ASHRAE Standard 62 [ASHRAE 1981] has a guideline for the maximum formaldehyde concentration of 0.1 ppm. The measured concentrations in this building are well below this level.

3.3.5 Radon

Although radon and radon decay products (progeny) within the building will not lead to occupant complaints of discomfort, elevated concentrations are certainly a matter of concern in terms of long term health risks. Radon and radon progeny levels were measured within the building in order to determine whether or not elevated levels existed in this building. The results of these measurements are shown in Table 5. The radon concentrations were measured at fifteen locations within the main complex and at three

additional locations in Building E-1. Radon progeny or working levels were measured at two locations within the main building, one of them being one of the basement mechanical rooms (BA301). The air exchange rates during the measurements in the main building were typically 1.5 to 2 air changes per hour. As mentioned earlier, air exchange rates were not measured in the E-1 building.

All of the measured radon concentrations in the main building were at or below the minimum detectable level of the charcoal canisters used to make the measurements, 0.4 pCi/L. The radon progeny levels were similarly quite low. Of particular significance is the low level found in the basement mechanical room. Lower levels of buildings are generally characterized by higher radon levels than the rest of the building. The fact that this essentially unventilated basement mechanical room is at such a low concentration is a strong indication of an extremely low radon source strength for this building. The measurements in the E-1 building were around 1.0 pCi/L, higher than the main building complex but still relatively low. ASHRAE Standard 62-1981 provides a guideline concentration for radon progeny of 0.01 Working Levels, which converts to a radon concentration of approximately 2.5 pCi/L. The 1989 revision contains a guideline concentration of about 7 pCi/L. The U.S. Environmental Protection Agency has an "action level" for radon of 4 pCi/L, meaning that some action should be taken in a building with concentrations above 4 pCi/L to reduce these concentrations. Therefore, the measured radon concentrations in this building are not a matter of concern.

3.4 Discussion of Air Exchange and Pollutant Measurements

The measurements of air exchange rates and indoor contaminant levels in this building enable a general characterization of this building as well ventilated and with pollutant levels that are not excessive with respect to the ASHRAE ventilation standard. The air exchange rates were always above the ASHRAE smoking and nonsmoking recommendations of 10 L/s (20 cfm) and 2/5 L/s (5 cfm) per person respectively, and were often more than twice the higher amount. All of the measurements made in this investigation indicate that the ventilation air is well distributed within the building interior, with no so-called "dead-spots" of poor air distribution identified. The low CO_2 levels in the building support the conclusion that the building ventilation rate is adequate relative to the building occupancy levels. The measured levels of CO, particulates, formaldehyde and radon were all also relatively low compared to the values in ASHRAE Standard 62. The episodes of elevated CO concentrations, while not high in comparison to the ASHRAE guidelines, are indicative of intake air quality problems, i.e., intake of motor vehicle exhaust from the loading docks. The existence of ground level intakes in this building, and the occupant complaints of odors, certainly makes intake air quality a matter of concern in this building. This issue, as well as other issues that may be related to the building's indoor air quality complaints, are discussed in the next section.

4. DISCUSSION

The results of the air exchange rate and pollutant concentration measurements discussed above are well within recommended levels, and therefore ventilation and indoor pollutant levels do not appear to account for the occupant complaints. This conclusion is necessarily based on current understanding of indoor air quality problems and the ASHRAE recommendations for ventilation rates and indoor contaminant levels. In the investigation of the building, other issues were uncovered that could explain some of the air quality complaints, i.e., intake air quality and thermal comfort.

4.1 Intake Air Quality

The existence of ground level intakes in this building may be associated with some of the indoor air quality complaints, particularly odors, due to the entrainment of various substances in the intake air. Referring to Table 1, the occupants have complained about odors such as motor vehicle exhaust and grass cutting, and this is not suprising given that the air intakes are located at ground level. It is recommended that ground level intakes should be avoided if possible, due to the stirring up of dust and debris by turbulence at ground level (ASHRAE 1989). Air intakes are commonly located on building facades, often a few stories above ground level or on the roof away from any exhaust vents. Referring to Figure 1, the air intakes for this building are located close to many sources of pollutants and odors including the loading dock, trash dumpsters, emergency generators, and the steam and chilled water plant. Figure 11 is a photograph of one such air intake, the large grille in the foreground (serving fans SL 5-10, see Figure 2). This photograph shows the close proximity to the intake of numerous motor vehicles, the loading dock (the opening on the right), trash dumpsters (in the background), and a building exhaust (hidden behind the column to the left of the loading dock). Figure 12 shows the loading dock, the exhaust grille, and the trash dumpsters more clearly. Further to the southeast of the loading dock are the building's emergency generators, which are tested regularly. Figure 13 is a photograph of these generators with the trash dumpsters and loading dock in the background. This photograph was taken during one of the periodic tests of these generators, and the generator exhaust is faintly visible in the photograph. On this particular occasion, the exhaust was flowing directly towards and subsequently into the air intakes on either side of the loading dock. Qualitative testing was done in which tracer gas was released at the loading dock to simulate a pollutant source, and the tracer was detected at the nearby air intakes and within the building.

In addition, the numerous building exhausts are also located at ground level, creating the potential for the entrainment of building exhaust air into the ventilation system's air intakes. The situation is further complicated by the fact that the building sits in a low lying area in comparison to the immediate terrain. Under appropriate wind and temperature conditions, pollutants generated by the various sources associated with the complex may

not be readily dispersed by the wind and remain in the proximity of the building for a longer period of time than they otherwise would, thereby increasing the chance that these substances are brought into the building by the air handling system.

Intake air quality problems are very difficult to assess since they tend to be episodic and variable in terms of their severity. Their occurrence in this builidng was demonstrated by the episodes of elevated CO concentrations in building intakes and in the occupied space. The visual observation of exhaust from the emergency generators flowing to the air intakes provided additional verification of an intake air quality problem. Whether these, and other incidents, are merely issues of odor and occupant discomfort or whether there is an actual health concern cannot be stated. The measurements of CO and particulate measurements reported here did not reveal any excessive pollutant levels, but they can not be ruled out on other occasions. While the entrainment of building exhaust air or intake of other outdoor pollutants appears to create odor problems in this building, one can imagine certain circumstances under which undesirably high levels of contaminants from a health perspective could occur in the building.

Solutions to the intake air quality problems in this building must deal with the fact that the air intakes are located at ground level and address the sources of the pollutant. The entrainment of some of these contaminants by the air intakes could be reduced by modifications which essentially raise the level from which the intake air is provided. Barriers could be constructed around the intakes such that contaminants from ground level sources are not as readily entrained. These barriers would need to be on the order of at least one-story in height. Another option would be the installation of ductwork from the air intakes to a higher level that would also serve to reduce the intake of outdoor contaminants from ground level. An engineering and cost study should be conducted to investigate the merit of these approaches.

In addition to these intake modifications, the control of outdoor contaminant sources also needs to be considered. These sources include building exhaust air from the exhaust vents, motor vehicle exhaust from the loading dock, odors from the trash dumpsters, exhaust from the emergency generators and the power plant, and groundskeeping activities. Different control options exist for these various sources. There is little that can be done about the building exhausts, but moving the loading dock and the trash dumpsters away from the building and its intakes would be effective in reducing the impact of these sources. This option would involve constructing a remote receiving and trash facility, and the use of shuttle vehicles (preferably electric powered) to transport these materials to and from the loading dock of the main building. Rescheduling activities such as generator testing, grass cutting and fertilizing to times when the building is unoccupied, or the occupancy is very low, would reduce the effect of these necessary outdoor activities. Another option to deal with the intake air problem would be the use of air cleaning systems within the air handlers to remove the pollutants and associated odors. While the removal of particulates from air is a well-developed technology, with

standard procedures to evaluate the effectiveness of such air cleaning systems, the technology for the removal of gaseous pollutants is not as well-developed. Systems available for the removal of gaseous pollutants, but this technology is not yet well understood and the evaluation of such systems is not standardized. Such an approach would require a significant level of maintenance for the air cleaning equipment.

4.2 Thermal Comfort

Thermal comfort also affects the perceived air quality within a building, and it depends on air temperature, relative humidity, air speed, and the radiant temperature of surrounding surfaces. If these parameters are outside of certain limits, the building occupants will be uncomfortable. The complaints listed in Table 1 include poor air circulation and poor air distribution, which can be due to thermal comfort problems of high air temperatures and/or low air speeds. The tracer gas and CO_2 measurements in these spaces indicate that ventilation air distribution is not a problem. Instead, these spaces might have thermal comfort problems because of thermal loads that are above the design expectations and supply air levels that can not meet these loads. Some of these areas were converted from storage or other low occupancy spaces to offices, and the supply airflow rate may not be adequate to control the temperature given the increased thermal load due to the occupants and office equipment. The supply airflow rate may also be inadequate to control the relative humidity and to maintain a comfortable level of air speed. The amount of outdoor air is more than adequate, but the amount of supply air is not. Some of these areas attain air temperatures in excess of 25°C (77°F) late in the afternoon, and the occupants experience discomfort. At night, when the air handlers serving some of these spaces are turned off, the spaces do not necessarily cool off due to continued heat output from office equipment. In fact, in some of the offices the air temperature actually increases during the night. During the testing of the building, the air handler serving one of these spaces (BC115) was operated twenty-four hours a day for roughly two weeks. Under these circumstances, the space was cooled during the night and began the day at a reasonable temperature. The heat build-up during the day did not result in the high temperatures that occurred normally. The space was generally more comfortable and the occupant complaints were reduced.

While these observations are anecdotal, it appears that a thermal comfort problem exists in portions of this builidng. Additional monitoring of temperature, relative humidity, air speed and radiant temperature is necessary to document the existence of a thermal comfort problem with certainty. An analysis of the thermal loads in these spaces and the cooling being provided to them would then be appropriate. Thermal comfort problems can generally be solved through adjustment of building HVAC controls if the equipment has the capacity to meet the existing loads, or through modifications of the ductwork and the supply airflow rates to specific areas. The control of thermal loads within the space may also help in reducing the thermal comfort problems.

5. SUMMARY AND RECOMMENDATIONS

The investigation of the USGS building was intended to evaluate several physical aspects of the building's ventilation and air quality performance in order to determine whether they were associated with the indoor air quality complaints. Building air exchange rates were measured under a variety of building operation conditions and compared to recommended levels of ventilation in buildings. The indoor levels of several airborne substances were also measured and compared to relevant standards and guidelines. The pollutants that were studied include carbon dioxide, carbon monoxide, radon, formaldehyde and respirable particulates.

The measurements of air exchange rates and indoor contaminant levels in this building enable a general characterization of this building as well ventilated and with pollutant levels that are not excessive. The air exchange rates are always above the ASHRAE smoking and nonsmoking recommendations of 10 L/s (20 cfm) and 2/5 L/s (5 cfm) per person and are often more than twice the higher amount. All of the measurements made in this investigation indicate that the ventilation air is well distributed within the building interior, with no so-called "dead-spots" of poor air distribution identified. The low CO_2 levels in the building support the conclusion that the building ventilation rate is adequate relative to the building occupancy levels. The measured levels of CO, particulates, formaldehyde and radon are all also relatively low compared to the values in ASHRAE Standard 62.

A small number of episodes of elevated CO concentrations, while not high in comparison to the ASHRAE guidelines, are indicative of a problem of intake air quality, i.e., intake of motor vehicle exhaust from the loading docks. The existence of ground level intakes in this building, and the occupant complaints of odors, certainly makes intake air quality a matter of concern in this building. The building also appears to have at least some thermal comfort problems that need to be studied further in order to verify their existence and to determine their extent.

Therefore, the air quality problems identified in this building concern intake air quality and thermal comfort. The intake air quality problems are associated with the building's ground level intakes and the pollutant and odor sources in proximity to these intakes. In order to eliminate these intake air quality problems, one should consider source control and/or relocation of the intakes. Source control could involve moving the trash dumpsters and loading dock away from the building and shuttling materials between the main building and such a receiving facility. Scheduling pollutant and odor producing activities (e.g., generator testing and grass cutting) to times when the building is not occupied is another source reducing action. Relocating the intakes is another option for improving the intake air quality. The ground level intakes are clearly part of the problem, and are generally not recommended. Extending the air intakes a few stories above ground level, or constructing barriers around the existing air intakes, are two such options and their use merits a thorough architectural and engineering analysis. The installation of air cleaning

equipment to remove both the particulate and gaseous pollutants from the intake air is a less attractive option. This equipment would be expensive in terms of installation and maintenance, and it is not clear as to how effective it would be.

In order to deal with the thermal comfort problems in the occupied space, there should be an engineering analysis of the thermal loads and cooling capacity in the spaces with thermal comfort complaints. Modifications in supply airflow rates, and perhaps fan on-times, may be necessary to correct these defects.

6. ACKNOWLEDGMENTS

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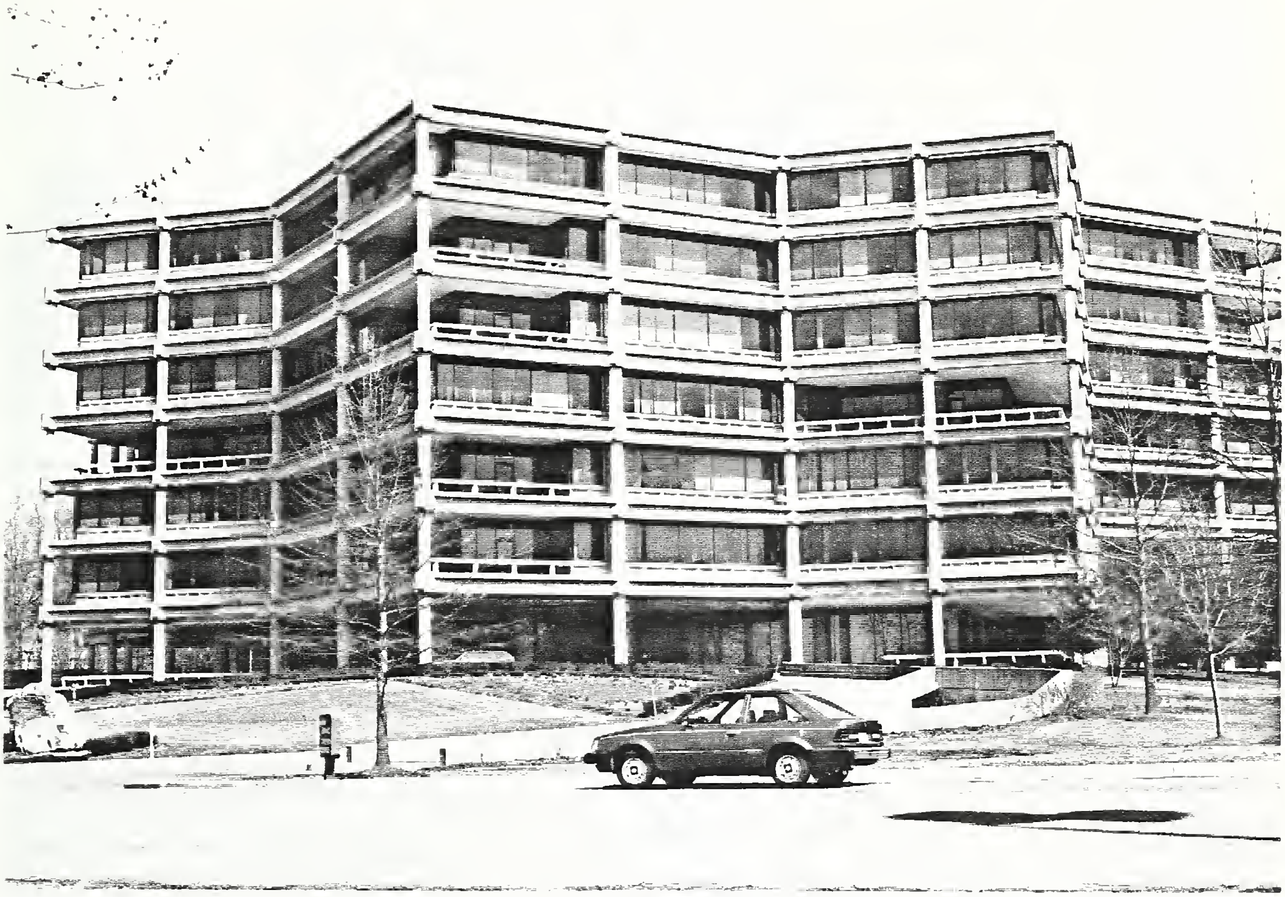

Figure 1: Photograph of the USGS Building

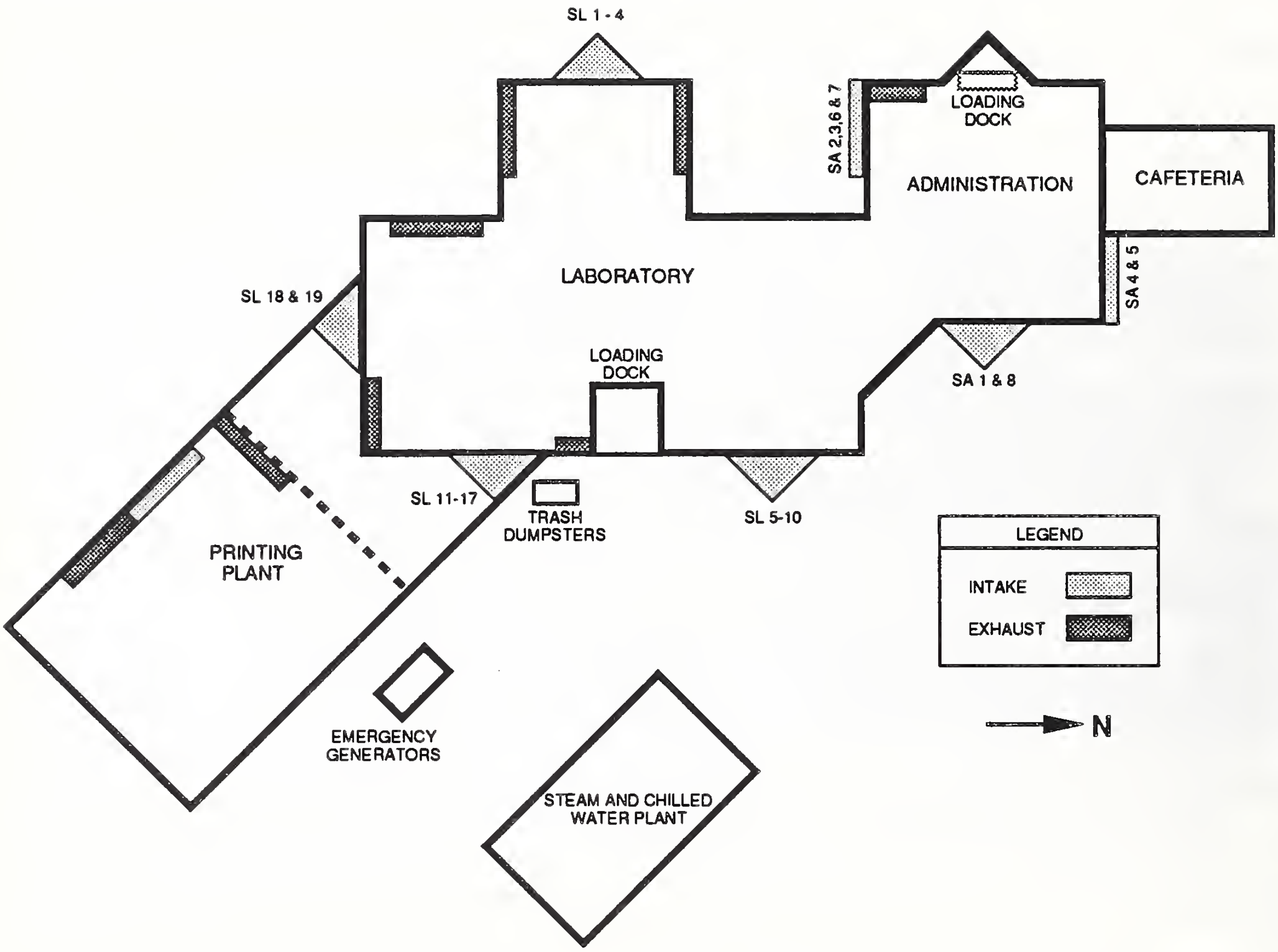

Figure 2: Schematic of Building Floorplan

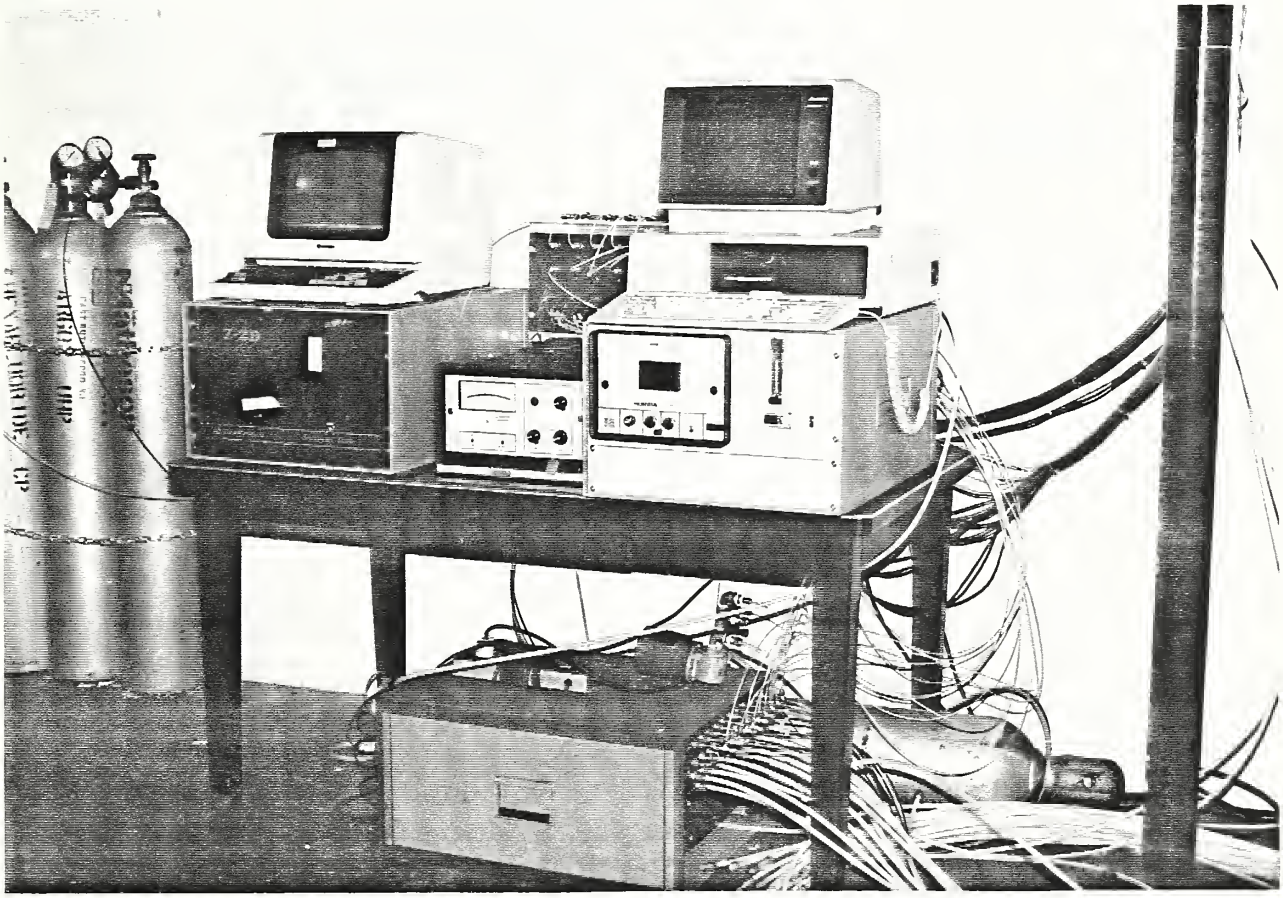

Figure 3: Photograph of the Tracer Gas Measurement System

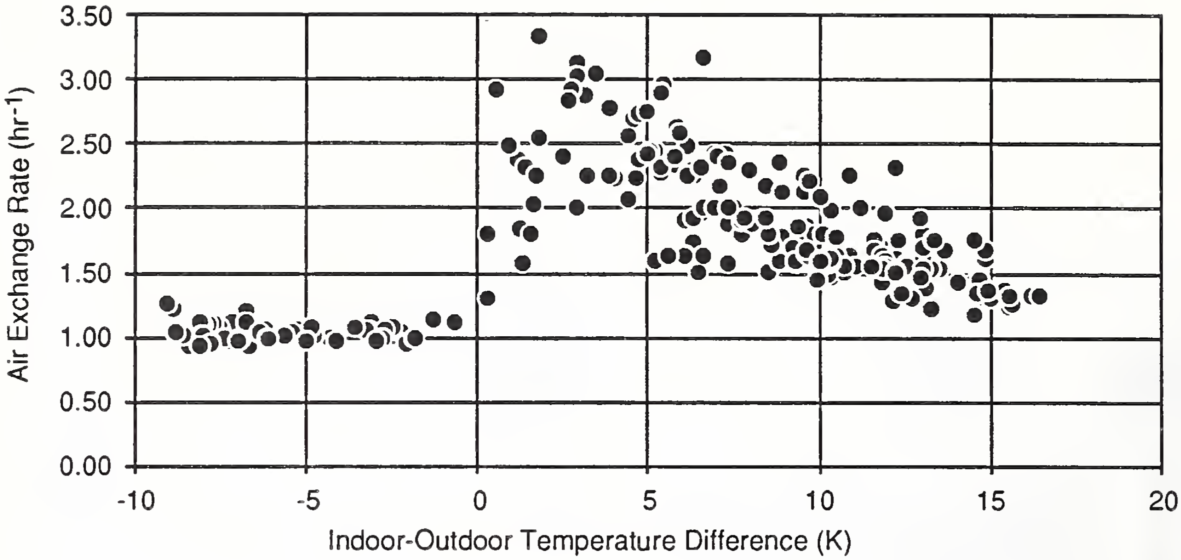

Figure 4: Measured Air Exchange Rates in Laboratory Section

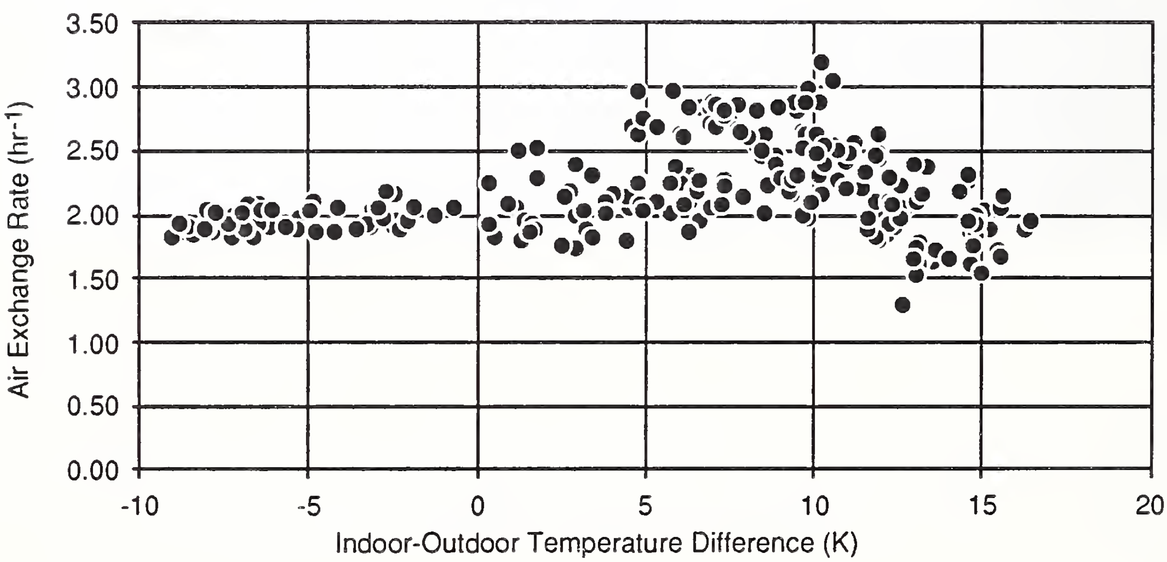

Figure 5: Measured Air Exchange Rates in Laboratory Section

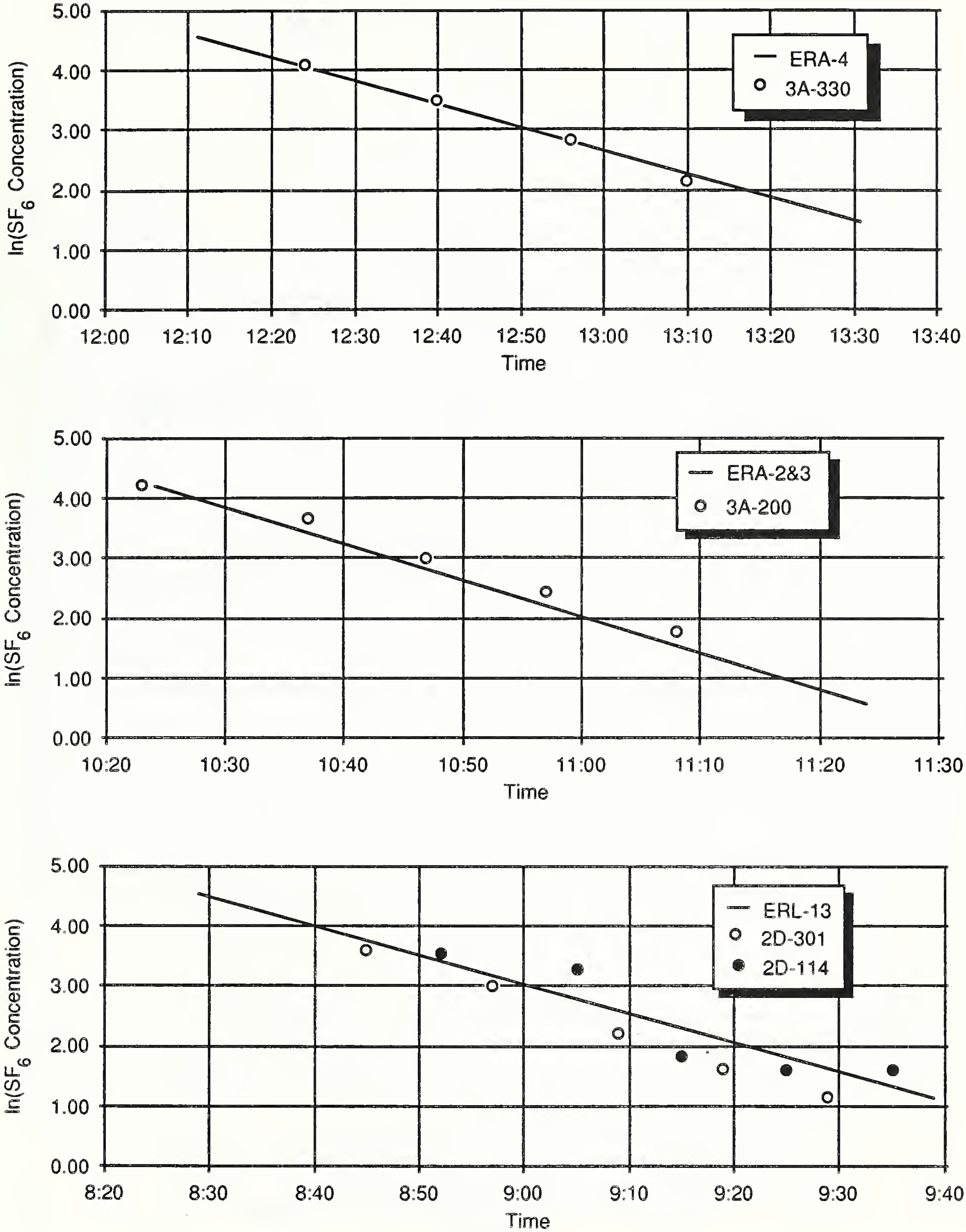

Figure 6: Local Tracer Gas Decay Results

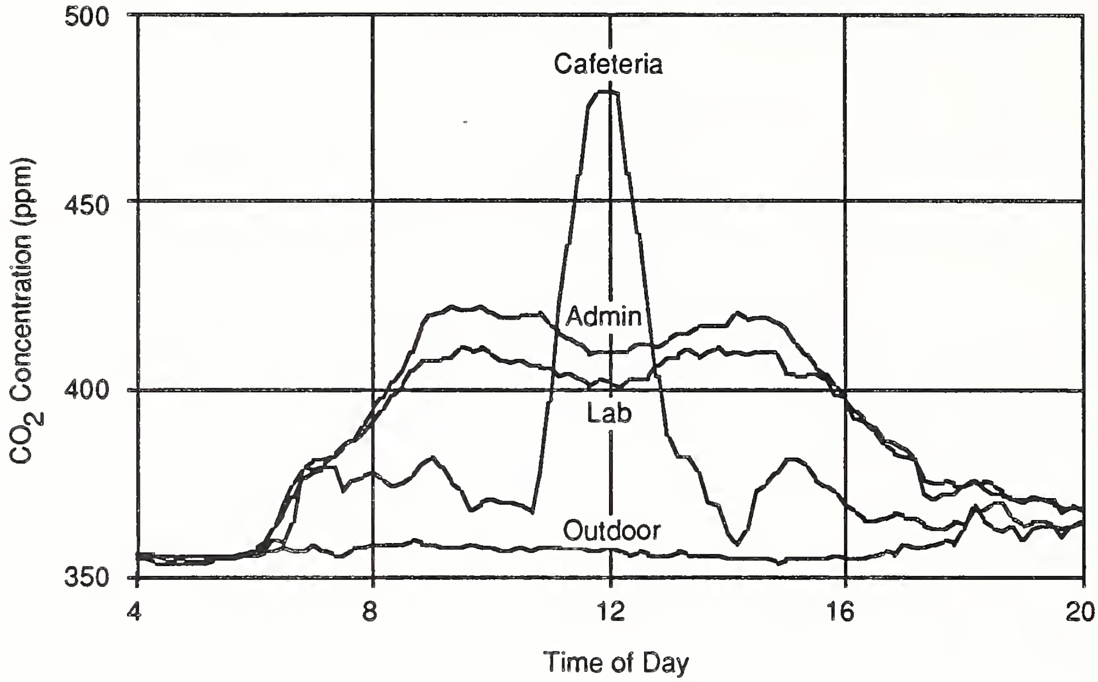

Figure 7: CO_2 Concentration During One Day

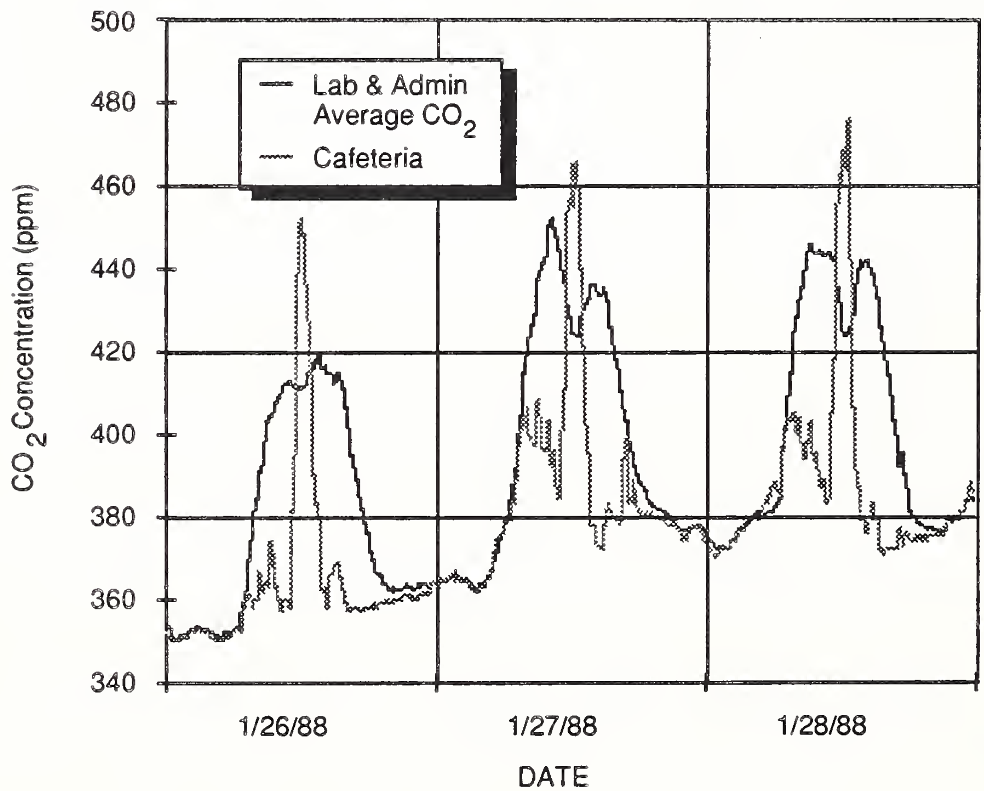

Figure 8: CO_2 Concentration Over Several Days

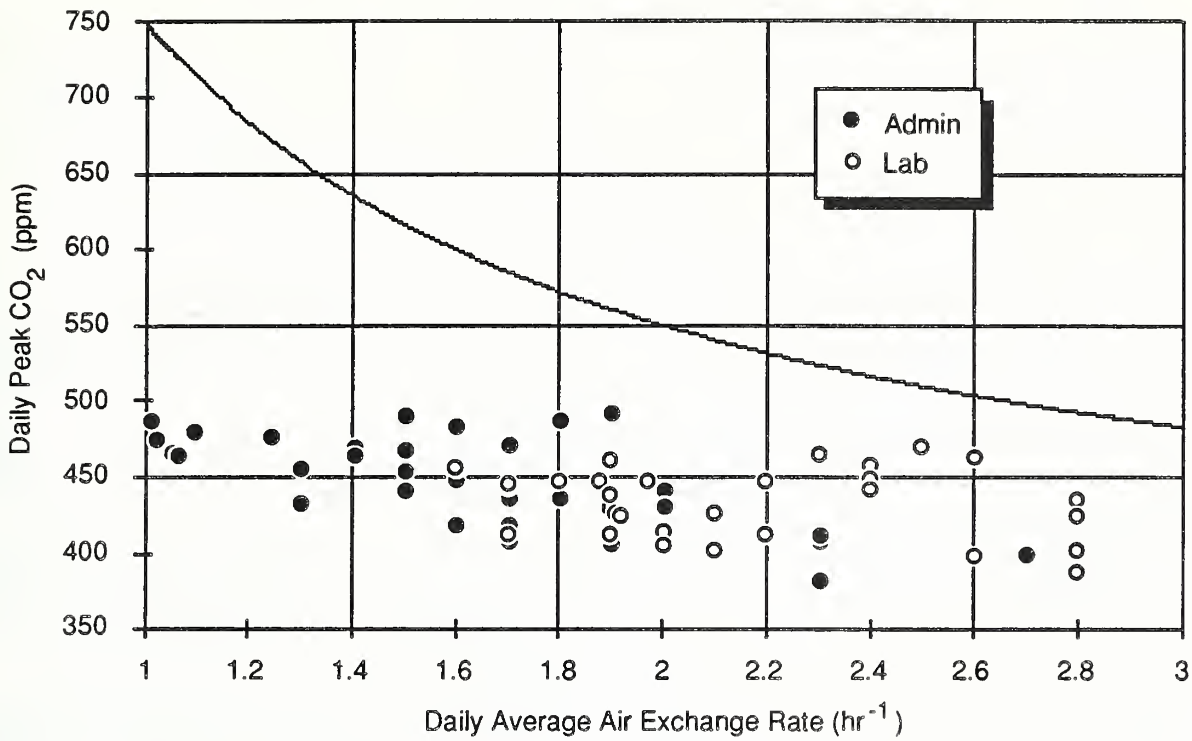

Figure 9: Daily Peak CO_2 Concentrations versus Daily Average Air Exchange Rates

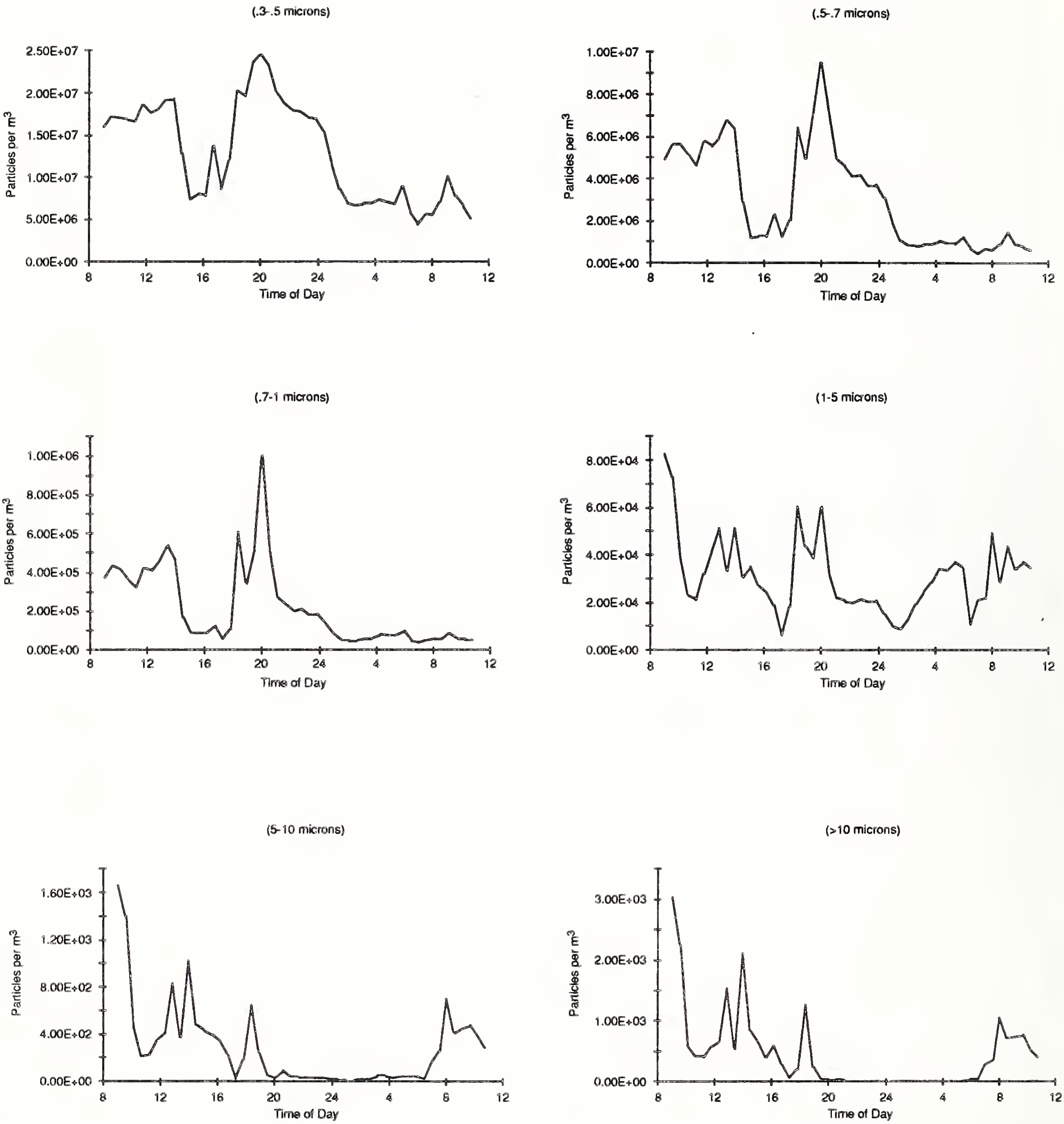

Figure 10: Example of Particulate Measurements

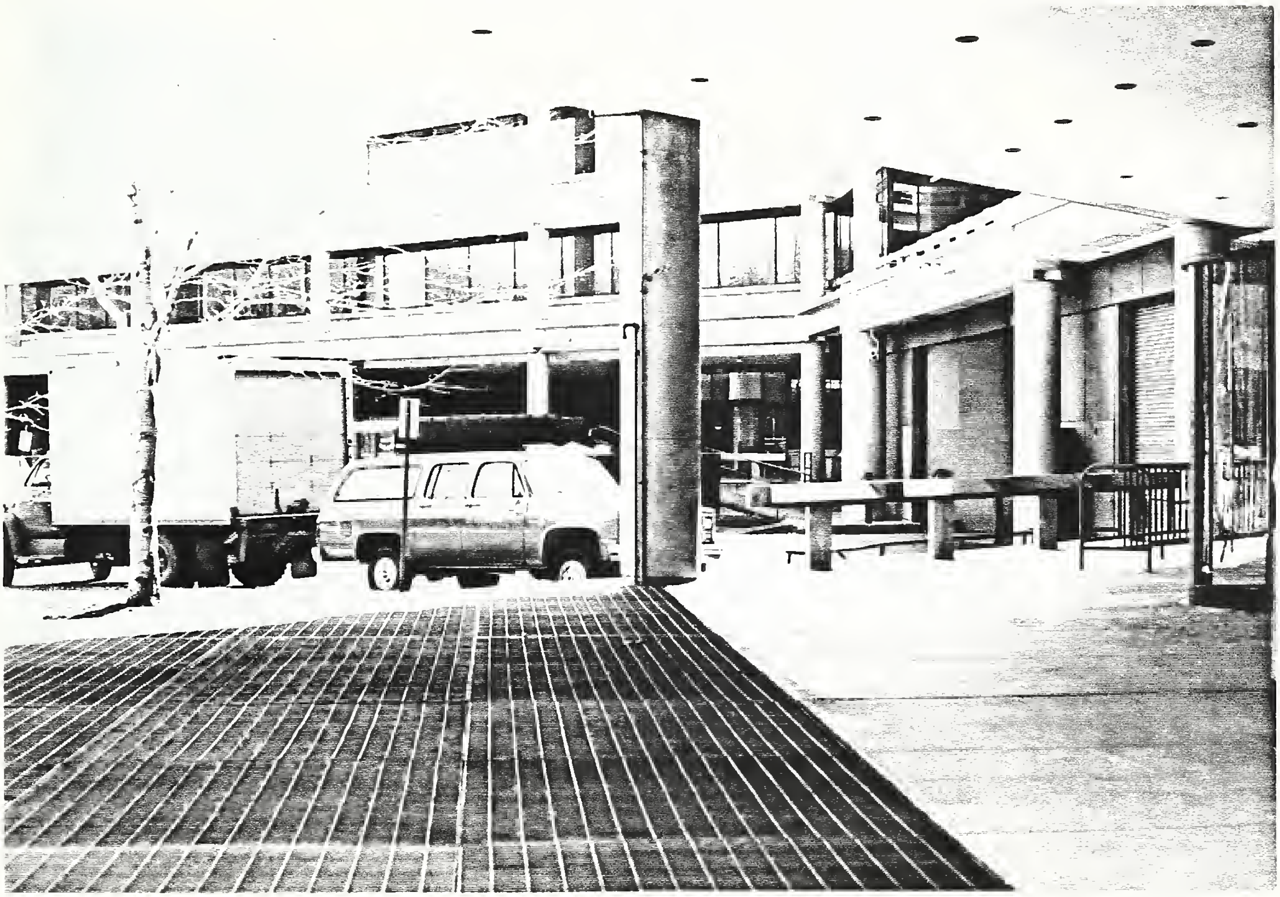

Figure 11: Photograph of Ground Level Air Intake

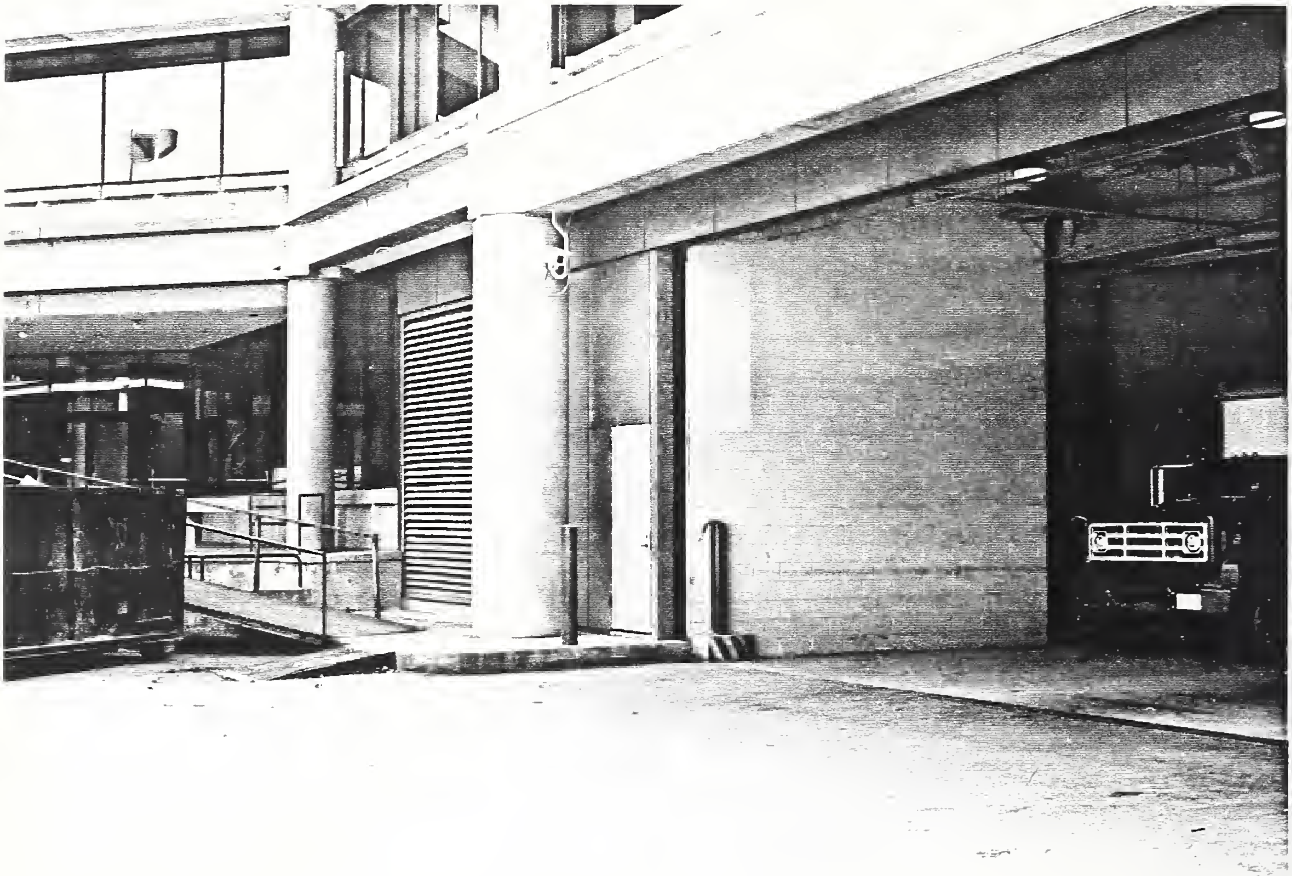

Figure 12: Photograph of Loading Dock, Exhaust Grille and Trash Dumpsters

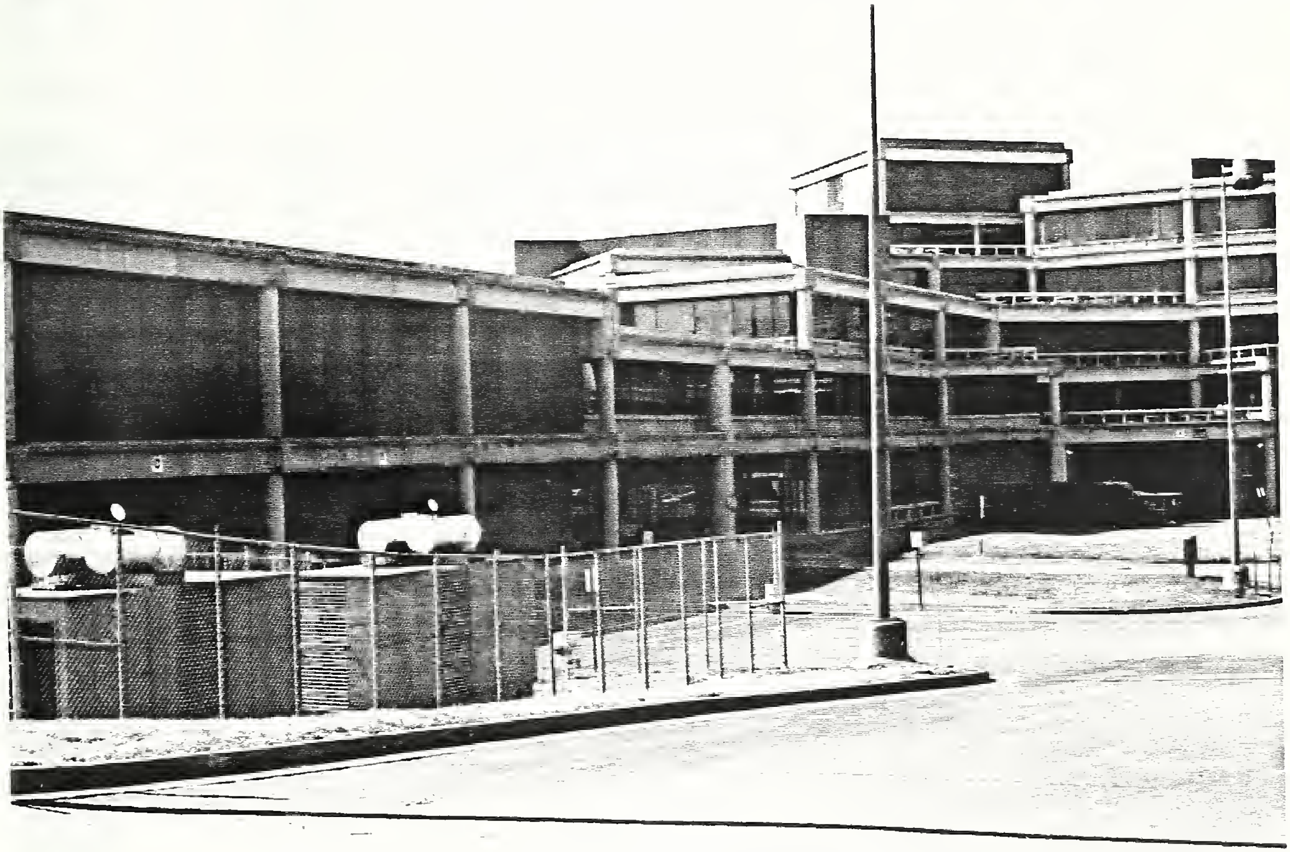

Figure 13: Photograph of Emergency Generators

Room #	Fan Serving Area	Comments
BC-101	SL-3	Requested testing - no reason given
BC-115	SL-3	Headaches, colds etc.
1B-205	SL-11	Headaches and eye irritation
2C-213F	SL-13	Requested testing - no reason given
2C-310A thru P	SL-2	Requested testing - no reason given
2C-310J	SL-2	Individual requested dust filter
2C401-J	SL-1	Requested testing - no reason given
2D-103J	SL-13	Headaches and crystalline-like growth on computer circuit board modules
2D-113 & 113A	SL-13	"
2D-114	SL-13	"
2D-301 & 301A	SL-13	Headache and nasea due to exhaust odors
2D-305A,B & C	SL-13	Exhaust fumes "on heavy air days"
3A-200	SA-2	Requested testing - no reason given
3A-205	SA-1	Requested testing - no reason given
3A-206	SA-1	Gas or grass clipping odors
3A-207	SA-1	Requested testing - no reason given
3A-330 thru 3A-341	SA-4	Headaches due to heat
3B-205	SL-1	Requested testing - no reason given
4A-101	SA-1	Poor air circulation
4A-104B	SA-2	"
4A-105	SA-1	"
4A-108A,B & C	SA-2	"
5A-339	SA-3	Poor air distribution and lack of fresh air
5A-409	SA-3	"
5A-411	SA-3	"
5A-413	SA-3	"
5A-415	SA-3	"
1P-119	ERP-3	Headaches and crystalline-like growth on computer circuit board modules

Table 1: List of Study Locations within the Building

Test	Location		Air Exchange Rate (hr^{-1})
#1 3/2/88	Return Fan Room	ERL-1 2C401	2.77 3.88
	Return Fan Room	ERL-2 2C310	3.63 3.32
	Return Fan Rooms	ERL-2 2C310 2C310A 2C310J	3.21 3.85 3.69 4.54
	Return Fan Rooms	ERL-13 2D301 2D114	2.95 3.41 3.15
#2 3/4/88	Return Fan Room	ERA-1 3A205	2.46 2.30
	Return Fan Room	ERA-2&3 3A200	2.30 2.43
	Return Fan Room	ERA-4 3A330	2.35 2.54
#3 3/24/88	Return Fan Room	ERA-1 Library SE	2.14 2.62
	Return Fan Rooms	ERA-2&3 4A104 4A108 Library SW	3.18 2.86 4.47 3.73
	Return Fans Room	ERA-4 ERA-2&3 Library N	2.57 3.18 3.30

Table 2: Results of Local Decay Tests

			Concentration (Number of Particles/m^3 x1000)					
			Particle Diameter (microns)					
Location	Date	Time	>10	5 - 10	1 - 5	.7 - 1	.5 - .7	.3 - .5
BC115 (copy area)	4/24/87	11:20-11:30	1.45	1.00	57.6	95.9	1030	8810
	4/24/87	14:30-14:40	1.05	0.81	57.5	126.0	1500	8510
	6/2/87 through 6/3/87	8:10 10:15	0.54	0.33	47.6	71.6	8040	22700
BC115 (conference room)	6/4/87 through 6/5/87	9:00 10:45	0.45	0.29	31.4	219.0	3120	12900
B213	4/24/87	10:55-11:05	1.44	0.97	145.0	439.0	4880	21200
BC113	4/24/87	11:35-11:40	1.44	1.14	89.7	118.0	1110	9150
Cafeteria Entrance	4/24/87	11:55-12:35	1.40	0.56	128.0	1240.0	10200	25100
1A315	4/24/87	12:55-13:00	2.78	1.27	80.8	199.0	1900	12400
2D115	4/24/87	13:15-13:20	1.18	0.88	179.0	799.0	5050	19800
2D113 (Computer Room)	4/24/87	13:25-13:35	0.88	0.48	26.2	51.1	556	5200
4th Floor Freight Elev. Lobby	4/24/87	13:50-13:55	5.70	1.80	86.5	919.0	8840	22700
5B134	4/24/87	14:05-14:20	1.48	0.79	90.5	511.0	5110	18600

Table 3: Results of Particulate Measurements

LOCATION	FORMALDEHYDE CONCENTRATION (ppm)	SAMPLE PERIOD
BC115	0.012	2/22/88 - 2/26/88
BC305	0.009	"
CAFETERIA	0.013	"
1A315	0.005	"
1B205	0.005	"
2P140	0.021	"
4A104	0.005	"
4C221	0.005	"
5A127	0.014	"
5B128	0.026	"
7A213	0.008	"
BC315	0.020	10/31/88 - 11/4/88

Building E-1

Rm 11 (hall)	0.020	7/25/88 - 7/29/88
Rm 20	0.020	"
Rm 35 (hall)	0.010	"
Rm 36	0.050	"
Rm 42	0.030	"
Bay Area	0.030	"

Table 4: Results of Formaldehyde Measurements

Charcoal Canister Measurements

LOCATION	RADON CONCENTRATION (pCi/L)	SAMPLE PERIOD
BA200	0.4	1/12/88-1/15/88
BA300	less than 0.4	"
BA301	less than 0.4	"
BB308	less than 0.4	"
BC100	0.4	"
BC301	less than 0.4	"
BC305	less than 0.4	"
1A102	less than 0.4	"
1D104	less than 0.4	"
2D301	less than 0.4	"
2D301	less than 0.4	"
3A204	less than 0.4	"
5A217	less than 0.4	"
7A203	less than 0.4	"
Printing Plant	less than 0.4	"
Building E-1		
Rm 1	0.8	1/19/88-1/22/88
Rm 13	1.0	"
Rm 35A	0.9	"

Working Level Monitor Measurements

LOCATION	RADON CONCENTRATION Average WL [pCi/L]	SAMPLE PERIOD
BA301	.000904 [0.23]	1/15/88 - 1/19/88
1A102	.000657 [0.16]	1/19/88 - 1/22/88

Table 5: Results of Radon and Working Level Measurements

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5. AUTHOR(S)

W. Stuart Dols, Andrew Persily

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

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Reston, VA

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The National Center of the U.S. Geological Survey in suburban Washington, DC is a seven story building containing both office and laboratory space. Based on a history of occupant complaints regarding the air quality within the building, an investigation was conducted by the National Institute of Standards and Technology to quantify the ventilation characteristics of the building and to determine the indoor levels of selected indoor pollutants. The investigation of the building included measurements of air exchange rates using the tracer gas decay technique and measurements of indoor concentrations of carbon dioxide, carbon monoxide, radon, formaldehyde and particulates. The measurement results are compared to appropriate standards and guidelines in order to investigate the role of ventilation and pollutant concentrations in the indoor air quality complaints. The additional issues of local distribution of ventilation air, entrainment of exhaust air, and thermal comfort were also examined. Based on the investigation, several recommendations are made to improve the environmental conditions within the building.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

air quality; building diagnostics; building performance; indoor air quality; tracer gas testing; ventilation.

13. AVAILABILITY

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